Imaging Tree Root Systems *In Situ*

Lucian Wielopolski, George Hendrey
Brookhaven National Laboratory, Department of Applied Science, Upton NY. 11973, USA.
Lwielo@bnl.gov   Hendrey@bnl.gov

Jeff Daniels
Ohio State University Department of Geological Sciences, Columbus, OH. 43210, USA.
jdaniels@geology.ohio-state.edu

Michael McGuigan
Brookhaven National Laboratory, Information and Technology Division, Upton NY. 11973,USA.
Mcguigan@bnl.gov

ABSTRACT

Prediction of global energy use in this century suggest a continued increase in carbon emissions and rising concentrations of carbon dioxide (CO_2) in the atmosphere. This represents a serious environmental problem and contributes significantly to greenhouse gases that affect global warming. Terrestrial ecosystems are a huge natural biological scrubber for CO_2 currently sequestering, directly from the atmosphere, about 25% (~2GtC) of the 7.4 Gt of anthropogenic carbon emitted annually into the atmosphere. The major carbon pathways into soil are through plant litter and roots. Presently, there are no means by which root morphology, distribution, and mass can be measured without serious sampling artifacts that alter these properties. The current methods are destructive and labor intensive.

Preliminary results using a high frequency, 1.5 Ghz, impulse Ground Penetrating Radar (GPR) for non-destructive imaging of tree root systems *in situ* are presented. The 3D reconstructed image is used to assess root morphology and dimensions. The constraints, limitations, and potential solutions for using GPR for tree root systems imaging and analysis are discussed.

INTRODUCTION

There is growing concern that increased levels of atmospheric carbon dioxide (CO_2), due to anthropogenic activities, lead not only to changes in earth's climate system through the greenhouse effect, but also may alter ecological balances through physiological effects on vegetation (Sarmiento, 1999). In the last decade, understanding of carbon cycle sources and sinks has advanced enormously and the importance of the terrestrial biosphere as a carbon sink has emerged. This opened the possibility that rates of terrestrial carbon sequestration may be intentionally managed over the next few decades to increase the amount of carbon stored in vegetation and soils.

Terrestrial ecosystems, which are made up of vegetation and soils containing microbial and invertebrate communities, are huge natural biological scrubber for CO_2 which currently sequester, directly from the atmosphere, about 25% (~2GtC) of the 7.4 GtC emitted annually into the atmosphere by human activities. Storage of carbon and changes in the storage of carbon in soil derive from the carbon content of plant roots, plant litter (undecomposed organic matter on the soil surface), humus in the mineral soil, and in some cases soil carbonate. However, the major source of the soil carbon is photosynthesis that results in active carbon transport to the soil through the root systems, and litter. These pools of carbon are several times larger than the pool in terrestrial vegetation above-ground, (Batjes, 1996, Schlesinger, 1977) and they are subject to change as a result of human activities and global climate change. Nevertheless, root systems, being an integral and critical part of carbon fixation following photosynthesis, have no direct measure at present (Taylor, et al., 1991).

Methods to assess changes in the storage of carbon in soils and in the root system mass are plagued by the extreme spatial variability of soils and the intensive labor required to sample roots. There is a need for *in situ* non-destructive sensors to quantify belowground rates and limits of carbon accumulation, both spatially and temporally, and to measure changes in root system mass.

It is proposed to use a high frequency Ground Penetrating Radar (GPR) for non-destructive imaging of tree root systems *in situ*. The method is non-destructive and non-invasive. Three-dimensional (3D) images of roots, *in situ,* can be obtained from GPR data using software developed for other applications. The 3D reconstructed images can be used to assess root morphology, growth rate, surface area, volume, and mass. Preliminary results, using off-the-shelf equipment (1.5 Ghz impulse unit) and software, clearly demonstrate the feasibility of the proposed methods for tree root systems imaging. Although significant further work is required to improve images of the root systems, the physics of GPR is sufficiently well understood to allow confidence that further developments in hardware and software will definitely improve the imaging capabilities of GPR systems. In contrast to the work by Hruska (1999), where he created a wire mesh diagram of a tree root system using a 400MHz GPR, work described here reconstructs 3D images of root systems. Preliminary result of a 3D reconstructed tree root is presented, and the constraints, limitations, and potential solutions for using GPR for tree root systems imaging and analysis are discussed.

GPR SYSTEM AND THE SETUP

GPR is an established technique that has been used worldwide for over 30 years (Daniels, 1989; Peters, et al., 1994; Daniels, 1997) to locate objects underground, including pipes, barrels, drums, and other engineering and environmental targets. A basic GPR system is based on the principle that the propagation velocity of electromagnetic energy in the radio frequency range (approximately 10^7 to 10^{10} Hz) is a function of the electric permittivity of the material. When an electromagnetic wave emitted from a small surface transmit antenna encounters a boundary between objects with different permittivities, then it will reflect, refract, and/or diffract from the boundary in a predictable manner. Some of the reflections from the boundary return to the surface and are recorded by a receive antenna. Roots with higher water content than the soil matrix provide the necessary permittivity contrast that is detected by GPR.

In our preliminary measurements to evaluate suitability of using GPR to image roots we used an off-the-shelf GPR unit with a 1.5 Ghz central frequency bi-static antenna. Without any special optimization of the unit it was used to detect buried objects in a large test sand box (8'x5'x3'), shown in Fig. 1, and was also deployed for studies in the field. For sensitivity testing purposes objects such as: a 1 mm metal wire, plastic tubes filled with water, and a fresh s 2.5 mm tree twigs to simulate fresh root, shown in Fig. 2, were buried in the sand box at different depths and measured using GPR.

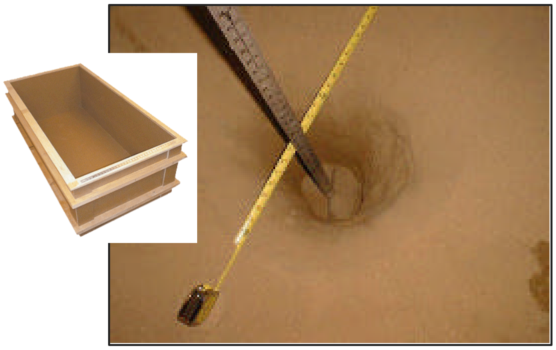

Figure 1. An empty sand box with a test hole.

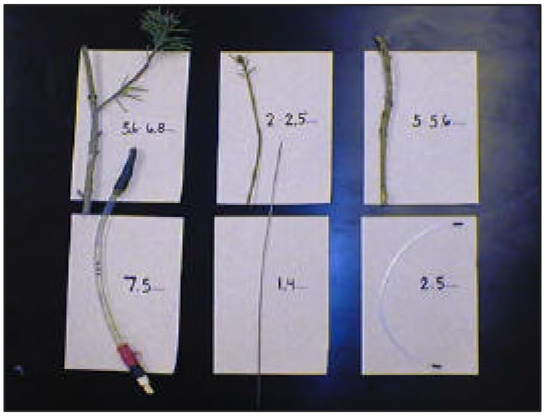

Figure 2. Objects that were buried at different depths to test the sensitivity of the GPR system.

The antenna was mounted to a small rectilinear frame with a survey wheel attached to it. This provided the two dimensional, xy position data set for the antenna that was used for image reconstruction purposes. This frame was used in the laboratory in the sand test box and in the field, (Fig. 3). Minimal signal processing was done during the scans. The vertical digital filters, Low Pass Filter was set at two poles and 3000 Mhz, and High Pass Filter was also set at two poles and 300 Mhz. In the horizontal digital filter all the parameters (poles and frequencies) were set to zero. There were 512 samples per scan and 60 scans per second, the range was set to 8.5 nsec. A raw scan of a 2.5 mm twig buried 25.4 cm deep is shown in Fig. 4, in which the typical hyperbola from the twig, with a maximum at approximate depth of 3 nsec, is clearly visible. The additional signal traces are due to reflections from the walls of the box.

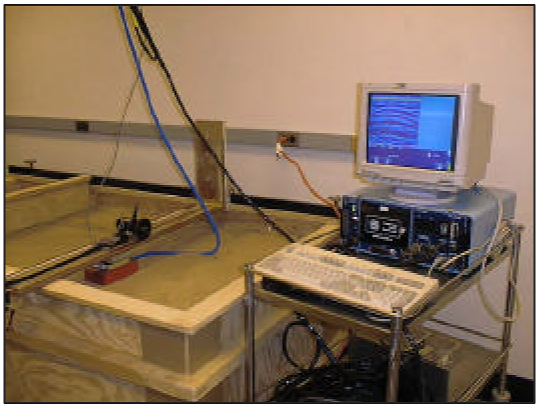

Figure 3. A two dimensional scanning frame with a survey wheel mounted on the sand box.

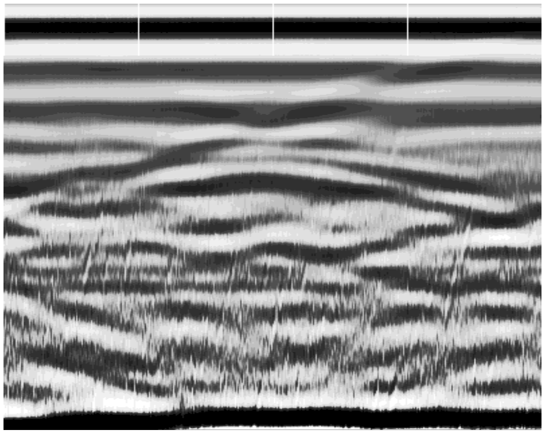

Figure 4. A raw scan of a 2.5 mm twig shown in Fig. 2 that was buried 25.4 cm deep. The peak is located at about 3 nsec from the surface.

The GPR unit was taken to a field site where using the same set-up, as for the sand box, two sets of 75 scans each in 2 cm intervals were taken over an area 0.8 m wide and 1.5 m long extending from the stem of a large apple tree. These two sets of data were scanned orthogonal to each other, i.e., the antenna was rotated 90 degrees to take advantage of the different polarization. Subsequently, the collected signal was processed with four digital filters to reduce the noise and clutter and prepare it for image reconstruction. These filters included a Horizontal Boxcar background removal and Stacking, Kirrchhoff migration of the signal in order to collapse the hyperbolas, and Hilbert amplitude transform to obtain positive values only for the image reconstruction. The slices of the processed data were arranged in order of scanning into a 3-D data cube that was transferred to image reconstruction software.

IMAGE RECONSTRUCTION

Following signal processing the GPR data cube was imported into OpenDX data explorer visualization software where it was treated as a 3D volumetric data set. In this process the data was treated as a tomographic data set, although physically the GPR signal is reflected from the interfaces only, thus creating an echogram. Two methods were used to visualize the roots from the data cube set: (1) thresholding- using the recorded strengths of the GPR signal the threshold level is set so that background signals are rendered invisible and the outline of a tree root is visualized. (2) Isosurfacing- using the marching cube algorithm for isosurface extraction (Cline 1988) the root image is reconstructed. However, although both algorithms provided similar results, the later has limitations in that artificial holes and bumps can be induced. In the future a dividing cube voxel subdivision method (Schroeder 1998) should be used for greater precision with fewer artifacts. Unlike marching cubes, dividing cubes makes use of points as primitive objects and with enough points a very smooth reconstruction is possible. This will prove important for small root visualization.

These reconstruction algorithms, conventionally used for medical images, were used in the present work just to demonstrate a proof-of-principle. It is well recognized that specialized filters that would discriminate clutter and other artifacts typical to GPR scans must be developed. For example, a connectivity filter that would eliminate noise (any feature that does not belong to the root image) contained in the isosurfaces extracted from the cube. The root system should present us with a large smoothly connected surface. For example, a recursive visit connectivity algorithm (Schroeder 1998) might be used to extract just the root system from noise and other underground structures that are disconnected from it.

A reconstructed image of the roots can be subjected to image analysis where, for example, the volume bound by an isosurface can be computed by counting the inner number of voxels. Combing this volume with the root gravimetric density will allow computation of- its mass and subsequently of the carbon content. A reconstructed image of a large root, from the data described above, and its volume are shown in Fig. 5.

Another important filter to develop will be depth corrections to accentuate the weak signals from deeper underground regions, and to obtain proper root thickness in the vertical direction which is affected by the propagation velocity. These techniques, once developed, will be applicable to other problems involving the conversion of echogram data to 3D tomographic visualization. A prime example of this is the application of ultrasound data for 3D medical visualization of the human body.

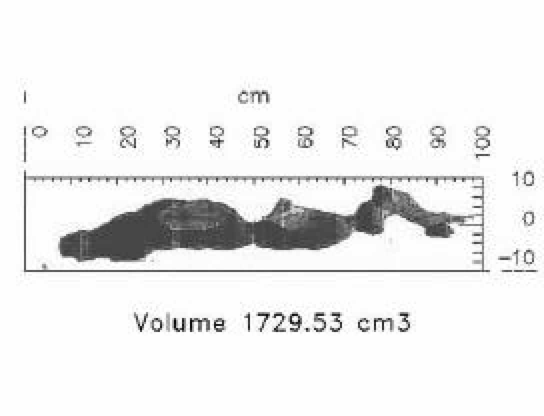

Figure 5. A visual reconstruction of an actual large tree root and the calculated volume.

DISCUSSION

The utility of a non-orthodox use of GPR to image tree roots has been presented. The GPR system and imaging software used for these measurements were not optimized in any way for root imaging. The purpose of using off-the-shelf equipment and software was to demonstrate a proof-of-principle. The depth in soil between 30 to 70 cm, usually discarded in geophysical measurements because of its noise content, is the region of main interest where the roots grow. Conflicting considerations between improved resolution with higher frequency, and depth penetration with lower frequency, require compromises that still need to be identified. It appears that a multifrequency antenna with 7 Ghz, 5 Ghz, and 3 Ghz might be required to cover a whole range of depths and resolutions capabilities. Also an array of multiple antennas with synthetic aperture might prove more efficient for scanning purposes and for enhancing the signal intensity.

The specific cylindrical shape of the roots invites the use of the polarization features of GPR to enhance the signal as well as to identify and to remove clutter from the scan. Designs of antennas with dual polarization are already appearing on the market. However, because of the convoluted nature of the root systems, antennas with multiple polarizability might be more advantageous.

In addition to hardware development, root detection can be further improved by optimizing and designing specialized filters for the electronic signal conditioning and processing. We did show that a 2.5 mm twig buried in sand can be detected, albeit under idealized conditions, thus indicating the detectability of a perturbation smaller in size than the wavelength of the pulse. With the apparatus and software used, however, it was impossible to determine its diameter at this size. For that purpose a continuity filters needs to be developed that will identify and remove local clutter from a root that is continuous, and at the same time ascertain its size assuming some gradients from roots with larger diameters. In addition iterative incorporation of Finite Difference Time Delay synthetic simulation of the EM propagation in the matrix and in the tree roots should assist in the reconstruction of root architecture, and should help to resolve some of the ambiguities that may arise as discussed above.

It is important to keep in mind that the measured signal constitutes an echogram and not a tomogram and that it must be handled accordingly. It is important to consider how the data is being prepared for reconstruction so as to avoiding creating artifacts.

In summary, the presented results demonstrate the utility of GPR to image tree root systems. With current technical capabilities and future developments, it is realistic goal to image roots 2 to 3 mm in diameter. In any event, information on roots *in situ* of the sort presented in this paper could be og great value to soil and root scientists.

ACKNOWLEDGMENT

This research was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

REFERENCES

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47, 151-163.

Cline HE., Lorensen WE., Ludke S., Crawford CR., and Teeter BC., 1988, Two algorithms for the Three-Dimensional construction of tomograms. Medical Physics. 15(3): 320-327.

Daniels, J.J., 1989, Fundamentals of Ground Penetrating Radar: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, March 13-16, 1989, Golden, CO.

Daniels, J.J., Grumman, D.B., and Vendl, M.A., 1997, Coincident antenna three-dimensional GPR: J. Env. Eng. Geophy., 2(1): 1-9.

Hruska, J., Cermak J., and Sustek S., 1999. Mapping tree root systems with ground penetrating radar, Tree Physiology 19: 125-130.

Peters, L., Daniels, J.J., and Young, J.D., 1994, Ground Penetrating Radar as a Subsurface Environmental Sensing Tool: Proceedings of the IEEE, 82(12), Dec. 1994.

Sarmiento, JL and Wofsy, C (Co-Chairs), *1999, A U.S. Carbon Cycle Science Plan,* A report of the carbon and climate working group, U.S. Global Change Research Program, Washington DC.

Schlesinger, W.H. 1977. Carbon balance in terrestrial detritus. Annual Review of Ecology and Sytematics 8, 51-81.

Schroeder W., Martin K., and Lorensen W., 1998. The visualization toolkit. Prentice-Hall.

Taylor, HM, Upchurch, DR, Brown, JM, and Rogers, HH, 1991, Some methods for root investigation, in *Plant Roots and Their Environment*, McMichael, HM and Persson, H (eds), Elsevier Science Publishers BV, pp 553-564.